AFRL-PR-WP-TP-2003-204

DEVELOPMENT OF NICKEL ALLOY SUBSTRATES FOR Y-Ba-Cu-O COATED CONDUCTOR APPLICATIONS

Rama M. Nekkanti, Venkat Seetharaman, Lyle Brunke, Iman Maartense, Dave Dempsey, Gregory Kozlowski, David Tomich, Rand Biggers, Timothy Peterson, Paul Barnes, and Charles E. Oberly

OCTOBER 2003

Approved for public release; distribution is unlimited.

PROPULSION DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*: October 2003

2. REPORT TYPE: Journal Article Preprint

3. DATES COVERED *(From - To)*:

4. TITLE AND SUBTITLE: DEVELOPMENT OF NICKEL ALLOY SUBSTRATES FOR Y-Ba-Cu-O COATED CONDUCTOR APPLICATIONS

5a. CONTRACT NUMBER: F33615-98-D-2867

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER: 62203F

5d. PROJECT NUMBER: 3145

5e. TASK NUMBER: 32

5f. WORK UNIT NUMBER: Z3

6. AUTHOR(S)

Rama M. Nekkanti, Venkat Seetharaman, and Lyle Brunke (UES, Inc.)
Iman Maartense and Dave Dempsey (University of Dayton Research Institute)
Gregory Kozlowski (Wright State University)
David Tomich, Rand Biggers, Timothy Peterson, Paul Barnes, and Charles E. Oberly (AFRL/PRPG)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

UES, Inc.
4401 Dayton-Xenia Rd.
Dayton, OH 45432-1894

AFRL/PRPG

University of Dayton Research Institute
Dayton, OH 45469

Wright State University
Fairborn, OH 45324

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

10. SPONSORING/MONITORING AGENCY ACRONYM(S): AFRL/PRPG

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S): AFRL-PR-WP-TP-2003-204

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

To be published in IEEE Transactions on Applied Superconductivity, Vol. 11, No. 1, March 2001, pp. 3321-3324.

Report contains color.

14. ABSTRACT

Fabrication of long-length, textured substrates constitute a critical step in the successful application of coated high temperature superconductors (HTS). Substrate materials stronger than nickel are needed for robust applications, while substrates with non-magnetic characteristics are preferred for AC applications. The present work is thus focused on development of texture in high strength, non-magnetic substrate materials.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor) / 19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	10	Lt. Justin Tolliver / (937) 255-6343

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Development of Nickel Alloy Substrates for Y-Ba-Cu-O Coated Conductor Applications

Rama M. Nekkanti, Venkat Seetharaman, Lyle Brunke, Iman Maartense, Dave Dempsey, Gregory Kozlowski, David Tomich, Rand Biggers, Timothy Peterson, Paul Barnes and Charles E. Oberly

Abstract— **Fabrication of long-length, textured substrates constitute a critical step in the successful application of coated High Temperature Superconductors (HTS). Substrate materials stronger than nickel are needed for robust applications, while substrates with non-magnetic characteristics are preferred for AC applications. The present work is thus focused on development of texture in high strength, non-magnetic substrate materials. As the development of cube texture is easier in medium to high stacking fault energy materials, binary alloys based on nickel were evaluated for the present application. High purity alloys were melted and hot/cold worked to obtain thin tapes. The development of texture in these alloys as a function of processing parameters was studied by x-ray diffraction and metallographic techniques. Orientation Imaging Microscopy (OIM) was used to quantify the extent of texture development in these substrates. Results to date on the development of texture by thermo-mechanical processing of these alloys are presented.**

I. INTRODUCTION

High current densities (~10^6A/cm^2) were recently demonstrated in polycrystalline YBCO superconductors through the development of biaxial texture in the metallic substrate and then transferring the same epitaxially to the superconducting layer (1). An intermediate buffer layer is used to prevent diffusion of the metal into the superconducting layer, during high temperature processing. Several studies have determined that a sharp, reproducible cube texture can easily develop in face centered cubic (FCC) metals like copper and nickel, after appropriate thermo-mechanical processing (2). A potential therefore exists for an economical and scalable manufacturing process to fabricate long lengths of superconducting tape for various power applications.

Nickel has become the substrate of choice for coated conductor applications due to ease of achieving sharp cube texture as well as its chemical compatibility, along with lattice and thermal expansion match with diffusion barriers such as yttria stabilized zirconia (YSZ) or cerium oxide. However, its low strength in the recrystallized state requires delicate handling and cracks in superconductor can easily develop due to substrate stretching or bending, resulting in failure of the superconductor. The low electrical resistivity of nickel may also result in considerable eddy current losses for AC applications (3). The poor oxidation resistance of nickel becomes another concern during high temperature deposition of buffer layers by physical vapor deposition processes in an oxidizing atmosphere (4). The nature of the texture in the substrate changes from cube texture ((200) type) to (111) type due to formation of nickel oxide, which propagates to the superconducting layer through the buffer by epitaxy, thereby resulting in degradation of superconducting transport properties. In addition, the strong magnetic permeability of the nickel substrate may not be suitable for many superconductor applications due to drop in transport current densities in high magnetic fields (3).

As discussed above, a definite need exists for alternate textured substrate materials that are characterized by high strength, good oxidation resistance, high electrical resistivity and low magnetic permeability, compared to nickel. There are a number of nickel alloys available that satisfy the preceding requirements, but few studies have been carried out regarding development of texture in those alloys. The present work is focussed on development of texture in one such alloy for use as a substrate for YBCO coated conductor applications. Possible alternate substrate materials include Ni-Cr, Fe-Ni, Cu-Ni or ternary alloys like Ni-Cr-Al or Fe-Ni-Cr etc.

The deformation texture develops during plastic deformation of metals or alloys due to self induced crystal rotation of each grain. The recrystallization textures evolve when deformed metals are annealed at high temperatures. Stacking Fault Energy (SFE), γ, is a fundamental parameter controlling the type of deformation texture. Medium to high SFE metals or alloys ($\gamma >$ 100mJ/m^2) develop copper type deformation texture ({112} <111> orientation), which is ideal for the formation of cube texture during subsequent recrystallization annealing (5). It has been known for more than 60 years that heavy rolling reductions (>90%) and high annealing temperatures are needed to develop a sharp cube texture in FCC materials like Cu, Ni or Fe-Ni alloys. Heavy reductions are needed to create a large misorientation gradient surrounding a small cube nucleus in the deformation texture, appropriate for rapid growth on subsequent annealing. Only a qualitative understanding of the parameters affecting the evolution of texture has been documented. The important parameters in texture evolution are the purity, the starting texture, the type and amount of strain and the effect of grain growth following primary recrystallization (6).

II. EXPERIMENTAL

The recrystallization texture experiments were conducted on a number of binary alloys, based on nickel. The alloys of various compositions were melted from virgin metals in a vacuum induction furnace, and vacuum cast in square billets. The billets were hot isostatic pressed and then hot rolled to achieve a total reduction of 60% in thickness. After surface conditioning, the hot rolled plates

Manuscript received September 18, 2000. This work was supported by the U.S. Air Force Research Laboratories under Contract No # F33615-98-D-2867.

Rama M. Nekkanti, Venkat Seetharaman and Lyle Brunke are with UES, Inc.,Dayton, OH 45432.

Iman Maartense and Dave Dempsey are with University of Dayton Research Institute, Dayton, OH 45469.

Gregory Kozlowski is with Wright State University, Fairborn, OH 45324.

David Tomich, Rand Biggers, Timothy Peterson, Paul Barnes and Charles Oberly are with Air Force Research Laboratories, Wright Patterson Air Force Base, OH 45433.

were cold rolled to >90% reduction in thickness, in increments of 10% reduction per pass to achieve a final thickness of 0.07 to 0.10 mm.

For this study, results on one such alloy with a nominal composition of Ni-12 wt.% Cr are shown. Specimens were cold rolled to 95% reduction in thickness and then isothermally annealed at temperatures varying from 850^{0}C to 1350^{0}C for different lengths of time in a high vacuum atmosphere. The use of smooth rolls during the cold rolling step led to excellent surface finish of the rolled foils (surface roughness < 10 nm). The mechanical properties of some of the recrystallized alloys in thin sheet form were determined by tensile tests conducted on electro-discharge machined (EDM), dog-bone shaped specimens. The tensile axis was oriented parallel to the <100> axis. Magnetic measurements were performed by VSM at 77 K to determine the magnetic behavior. The macrotexture of rolled and annealed foils was characterized by X-ray diffractometry. The preferred orientation of the planes is determined by 'Two theta' scans, whereas the in-plane and out-of-plane textures were analyzed using Phi and Psi scans respectively. Orientation Imaging Microscopy (OIM) was performed on selected specimens showing good texture from X-ray diffraction experiments. Misorientation plots showing the grain fraction corresponding to each misorientation, pole figures and inverse pole figures were generated. .

III. RESULTS AND DISCUSSION

Table I show the results of tensile tests performed on rolled and annealed foils of pure nickel and selected binary alloys. For the purpose of this comparison, all the deformed materials were annealed

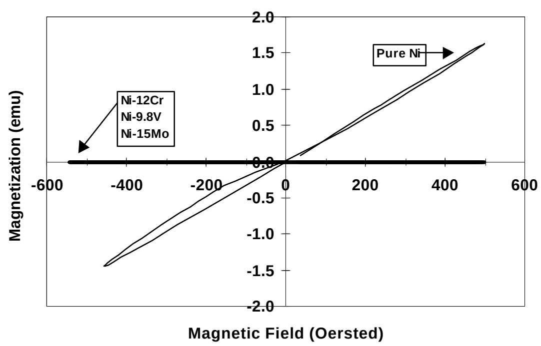

Fig. 1. Induced magnetization in Ni and Ni alloys at 77 K in a magnetic field

at 1100 ^{0}C for one hour. It is clear that both yield strength and ultimate tensile strength values of nickel alloys are substantially higher than those of nickel. Literature data on the electrical resistivity of these materials are also included in Table I (7). It is important to note that the electrical resistivity of these alloys is approximately one order of magnitude larger than that of nickel. Figure 1 compares the magnetization behavior of nickel and its alloys measured at the superconducting operating temperature of 77 K. It is clear that pure nickel exhibits a strong dependence of magnetization on the applied field, whereas the alloys show no magnetization at all. The Curie temperature of nickel alloy specimens is well below 77 K, indicating non-magnetic behavior at superconductor application temperature (77 K). This result is consistent with the reported data on the Curie point of Ni-20Cr and Alloy 625 being less than 77 K (7). The microtexture data obtained from the cold rolled specimens of pure nickel and Ni-Cr alloy are presented in the form of pole figures in Figures 2(a) and 2(b) respectively. The pole figures and the associated interpolated intensity data (in logarithmic scale) shown in Figure 2 (a) indicate the presence of different texture was observed components such as B, S and C. No evidence for the presence of cube texture component was observed.

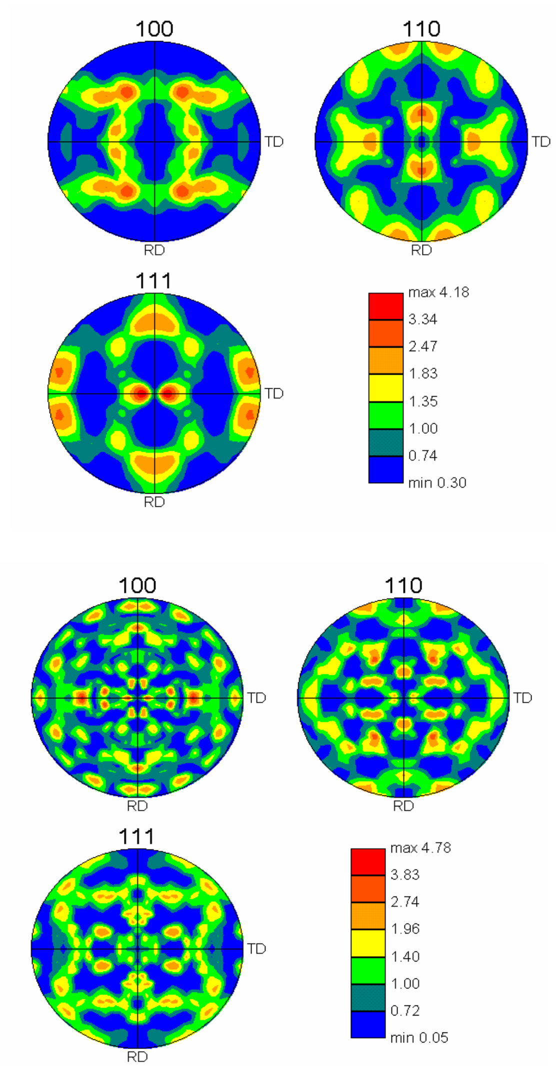

Fig. 2 . (100),(110) and (111) Intensity Pole Figures, in log scale of deformed (a) Pure Ni and (b) Ni-Cr alloy

TABLE I
PHYSICAL AND MECHANICAL PROPERTIES OF TYPICAL ALTERNATE SUBSTRATE MATERIALS

Material	Composition Wt.% (At.%)	Tensile Strength M Pa	Yield Strength M Pa	Electrical Resistivity nano Ωm
Pure Nickel		130	25.5	
Commercial Ni		203	51.1	95
Ni –Cr	12.0 (13.3)	336	84.9	1080
Ni-V	9.8 (11.0)	529	174.6	
Ni-Mo	15.0 (9.8)	709	272.6	

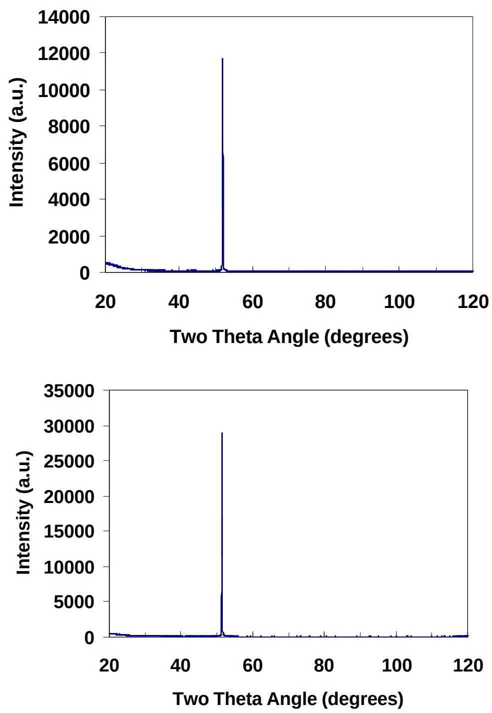

Fig. 3. Two theta scans on thermo-mechanically processed (a) Nickel and (b)Nickel-Chromium alloy

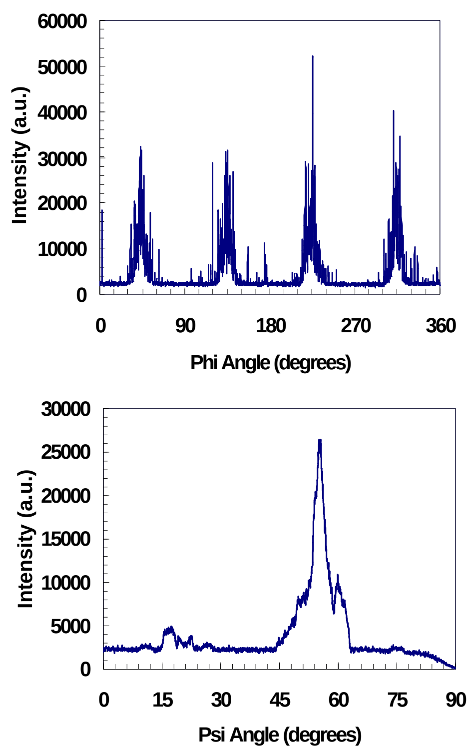

Fig. 4. Phi and Psi scans on textured Ni-Cr alloy heat treated at 900 ^{0}C for two hours in vacuum.

These results are in conformity with those reported by Goyal et al (8). The pole figures obtained from the Ni-Cr alloy in the as- deformed state (Figure 2(b)) are very complex and different from those shown in Figure 2(a), and require additional analysis and interpretation.

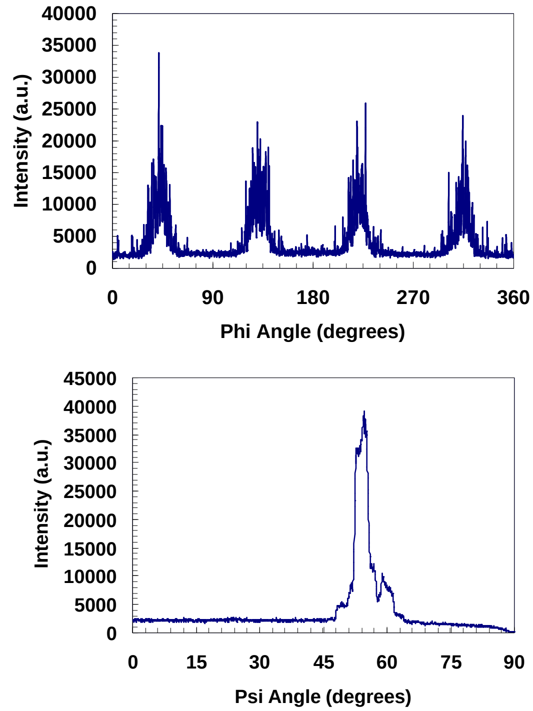

Fig. 5. (a) Phi and (b) Psi Scans on textured Ni-Cr alloy specimen heat treated at 1000 ^{0}C for two hours in vacuum.

X-ray diffraction two-theta scans were obtained from the deformed and recrystallization textured nickel and Ni-Cr specimens and are shown in Figures 3(a) and (b) respectively. Both exhibit very sharp (200) peaks indicating the development of cube texture in both materials.

The recrystallization textures (Phi and Pi Scans) shown in Figs. 4 and 5 were obtained from a nickel-chromium alloy sheet deformed to 95% reduction in thickness and heat treated at 900 ^{0}C and 1000 ^{0}C respectively for 2 hours in high vacuum atmosphere. The average values of FWHM of the peaks in Fig. 4 (a) and 5 (a) are 12.1^{0} and 10.1^{0}, respectively. Thus, a good reproducible, stable and sharp texture was developed in the Ni-Cr alloy after thermo-mechanical processing over a wide range of annealing temperatures. The apparent insensitivity of the recrystallization texture to heat treatment conditions constitutes a major advantage during manufacture and permits scale-up.

Psi scans were also performed in the above textured specimens and two of those scans corresponding to heat treatment at temperatures of 900 ^{0}C and 1000 ^{0}C are shown in Fig. 4 (b) and 5 (b). The evolution of texture is probably still proceeding in the specimen textured at 900 ^{0}C, as a second peak corresponding to (211) was observed in the psi scan (Fig. 4 (b)). The same would disappear if the specimen were heat treated for a longer time at the temperature, as the cube regions would grow by boundary migration and form a single texture. The specimen heat treated at 1000 ^{0}C did show almost a single texture and this suggests that the heat treatment temperature of 1000 ^{0}C and time of one hour are probably close to optimum conditions.

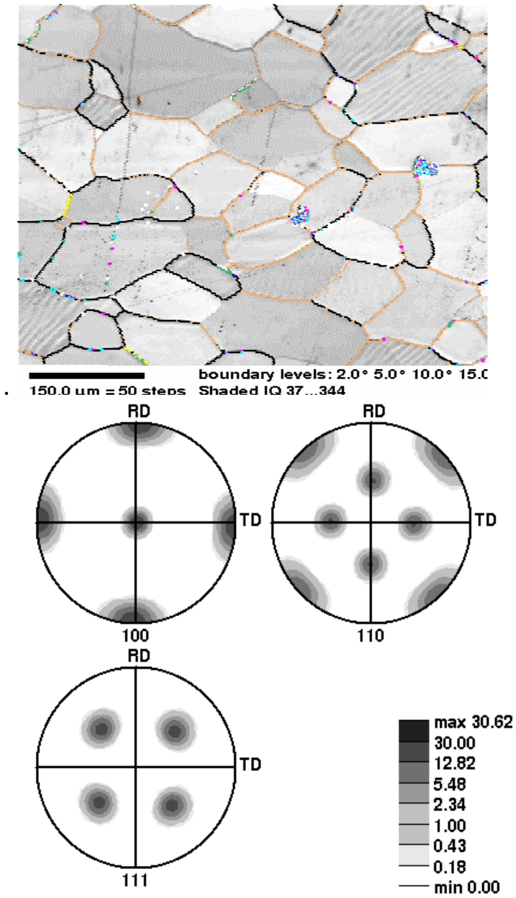

Fig. 6. OIM micrograph and pole figure plots of the textured pure nickel (Material was supplied by Eurus Technologies, Inc.)

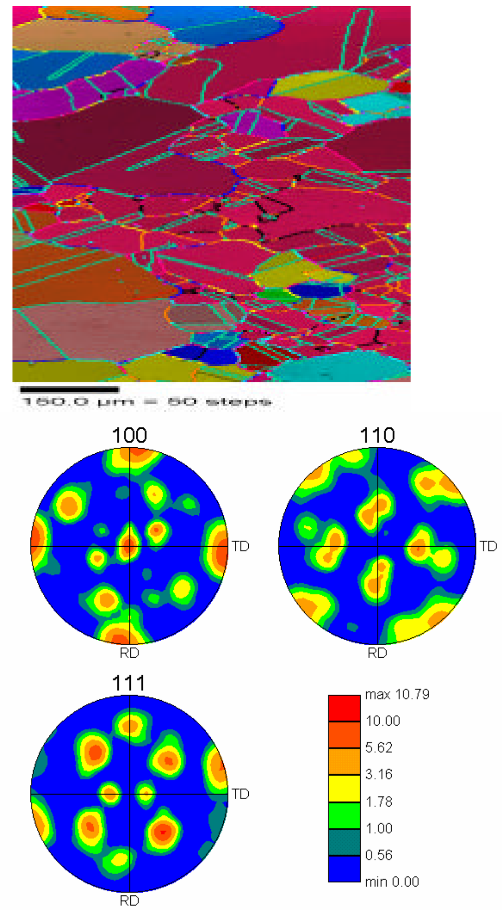

Fig. 7. OIM micrograph and pole figures of the textured Ni-Cr alloy.

OIM studies were performed on rolled and annealed specimens of pure nickel and the Ni-Cr alloy to compare the development of microtexture in these materials. The grain structures with rotation angle boundaries and pole figure data in each case are shown in Figures 6 and 7. The misorientation observed in the pure nickel specimen is minimal, as shown by a major fraction of rotation angle boundaries less than 10 degrees (Fig. 6). The grain structure in the case of the Ni-Cr specimen shows a number of twins, which results in multiple poles with twin orientation, and a decrease in the intensity of the cube orientation (Fig. 7).

A typical optical micrograph obtained from the recrystallized Ni-Cr specimen is shown in Figure 8. This microstructure is by and large free of twins and represents a desirable structure. Additional experiments to optimize the heat treatment temperature and time to obtain twin-free microstructures in Ni-Cr specimens are currently being pursued.

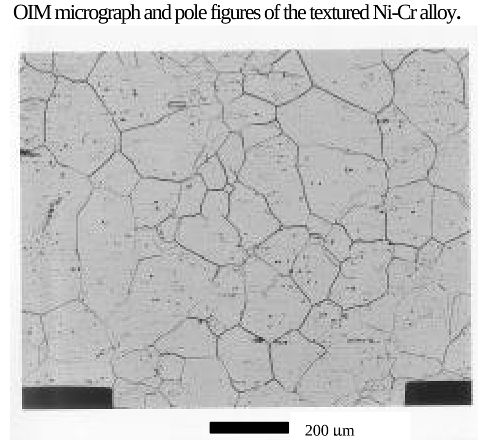

Fig. 8. Optical micrograph of the textured Ni-Cr alloy in 'as heat-treated' condition

In summary, alternate metallic substrates with better physical and mechanical properties compared to nickel have been identified for coated conductor applications. A reproducible, sharp and single cube texture with FWHM of ~10^0 can easily develop in nickel-chromium alloy after 95% cold reduction by rolling and heat treatment in the temperature range 900 ^{0}C to 1000 ^{0}C.

REFERENCES

1. A. Goyal et al, Appl. Phys. Lett. 69, (1996), p.1795
2. C. S. Barrett, *The Structure of Metals*, 2nd ed., New York: McGraw-Hill, (1952)
3. W. J. Carr, Jr. , private communication
4. D. P. Norton et al, Science, 274, (1996), p. 755
5. N. Brown, Trans. AIME, V. 215, (1961), p.530
6. F. Haessner, *Recrystallization of Metallic Materials*, 2nd ed., Stuttgart: Dr. Riederer Verlag GmbH, (1978)
7. ASM Metals Handbook, Vol. 9
8. A. Goyal et al, Micon 30, (1999), pp 463-478.